ANNUAL PROJECT SUMMARY

Assessing Seismic Hazard in Puerto Rico and the Virgin Islands Using the Historical Earthquake Record and Mixed-Mode GPS Geodesy: Collaborative Research Between the University of Puerto Rico, Mayagüez and the University of Texas at El Paso

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Element I
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SUMMARY

Data to assess seismic hazard in Puerto Rico and the Virgin Islands were obtained using Global Positioning System (GPS) geodesy. Measurements were collected at 21 campaign and 4 continuous sites. Emphasis is on quantifying surface displacement of active faults. Preliminary results derived from data from a subset of the existing GPS network are consistent with deformation on the island of Puerto Rico limited to less than a few mm/yr, including areas where active faults are proposed. Most of the active faulting occurs offshore north of the island of Puerto Rico, where displacements of 16 mm/yr must be accommodated.

INVESTIGATIONS UNDERTAKEN

Overview and background: Puerto Rico and the Virgin Islands (PRVI) have a long historical record (~400 years) of damaging earthquakes, including the 1916, 1918, and 1943 Mona Passage earthquakes (Ms=7.2, 7.3, and 7.5 respectively), the 1867 Anegada Passage earthquake (Ms=7.3), the 1787 Puerto Rico trench earthquake (M=7.5?) and the 1670 San German earthquake (M=6.5?)[(1)]. Current seismicity mimics the pattern of the large, historic events. Earthquakes are concentrated offshore Puerto Rico in the Mona and Passages, the Muertos Trough, and the Puerto Rico trench. The highest levels of onshore seismicity are in southwest Puerto Rico in the Lajas Valley, an EW-trending feature, which continues west offshore and passes south of the southern termination of the Mona Canyon.

During the last two decades, significant progress has been made toward assessing the seismic hazard of PRVI. This includes the establishment and continued enhancement of the Puerto Rico Seismic Network, the development of regional tectonic models, the recognition of microplate behavior in the northeastern Caribbean, the documentation of potentially active faults onshore and offshore, and the assessment of relative motion between the Caribbean and North America plates. Despite advances in the state of knowledge, however, key aspects of the fundamental geologic and geophysical underpinnings necessary to delineate seismic source zones for evaluation of seismic risk remain either largely unconstrained or controversial. These are summarized in three points.

- *What is the nature of deformation in the plate boundary zone near PRVI, i.e. does the zone contain distinct rigid blocks which move separately from one another or are displacements taken up continuously across its width in simple shear?*

- *Where are the active faults?*
- *What is the mechanical behavior of mapped and potentially active faults, i.e. are the faults locked and accumulating strain that must be released catastrophically during a significant earthquake or are the faults creeping aseismically?*

These questions must be answered to evaluate seismic risk quantitatively and to plan appropriately for development of civil infrastructure. The only published earthquake hazard map for Puerto Rico[(2)] for example, does not include calculation of the risk of rupture of specific faults because reliable data on deformation rates across seismogenic structures were not available. A 1999 draft USGS hazard map, which used the sparse GPS-velocity field in (3) to partition slip among various areal zones roughly coincident with mapped onshore and offshore features, yields probability for damaging ground motion in western Puerto Rico equivalent to that for Seattle, Washington.

Better definition of the possible seismogenic features within the northeastern Caribbean and their potential associated slip is essential to assessing earthquake hazard and establishing appropriate actions to mitigate seismic risk. One of the most powerful techniques to provide such data is Global Positioning System (GPS) geodesy, which can obtain positions of points on Earth's surface to a precision of a few millimeters. Changes in positions over time allow scientists to pinpoint locations of active faults, document their associated displacement and mechanical behavior, and model the deformation field to improve understanding of the potential for destructive earthquakes. GPS arrays now are an integral part of earthquake monitoring networks worldwide.

This project emphasizes the collection and analysis of surface deformation data obtained from mixed-mode Global Positioning System (GPS) geodetic studies, on-going in PRVI since 1994, to determine slip rates and strain accumulation along active structures in PRVI. The project is part of a collaborative study with the University of Texas at El Paso (UTEP) of historic earthquakes of M>6.0 occurring from 1906 to 1960 to identify possible seismogenic structures and to estimate how much of the deformation has been released seismically over the past 80 to 90 years. The existing PRVI mixed-mode GPS array consists of 4 continuous GPS sites and 21 campaign sites. Two continuous sites and 11 campaign sites were added as part of our USGS-NEHRP work. During the upcoming year, we plan to install two continuous GPS sites and an as yet undetermined number of campaign GPS sites, depending upon our preliminary results.

Tectonic setting: Puerto Rico and the Virgin Islands are located within the broad EW-trending boundary between the Caribbean and North American plates in the northeastern corner of the Caribbean (Figure 1). The boundary is characterized primarily by left-lateral motion along predominantly east-west striking faults. The eastern half of the boundary in Hispaniola, Puerto Rico and the Virgin Islands is a complex deformation zone ~250 km wide, whose northern and southern limits are defined by the Puerto Rico trench and the Muertos trough, respectively. Three proposed microplates lie within this diffuse boundary zone (Figure 1). From west to east, there are (1) the Gonave[(4)], (2) the Hispaniola[(5)] and (3) the Puerto Rico-northern Virgin Islands (PRVI)[(6)]. Such a microplate model assumes that nearly all of the deformation associated with North America-Caribbean motion is concentrated along the faults that bound the three rigid blocks: the Oriente, Septentrional, Enriquillo-Plantain Garden, and Anegada faults, the Muertos trough and North Hispaniola deformed belt, and the Mona rift faults northwest of Puerto Rico (Figure 1).

Global Positioning System (GPS) geodetic data from CANAPE (CAribbean-North American Plate Experiment) constrain motion of the Caribbean plate at Cabo Rojo in the southernmost Dominican Republic relative to North America as 20.6±1.2 mm/yr toward N89°E±3°[3]. Recent GPS-derived velocities relative to North America from the interior of the Caribbean plate at San Andres Island (12.524°N, 81.729°W) in the west and Aves Island (15.667°N, 63.618°W) in the east may be modeled with error, along with the Cabo Rojo velocity, using a single pole of rotation[7], supporting the assumption that the southern Dominican Republic is part of the rigid Caribbean plate.

On-land faulting: Prevailing scientific opinion is that PRVI remains rigid and that deformation occurs primarily on the bounding structures of the microplate. The question arises as to how rigid is "rigid PRVI"? Do faults exist within PRVI, particularly onshore, that are capable of producing significant and locally damaging earthquakes? The highest levels of onshore seismicity are in the southwest corner of Puerto Rico in the Lajas Valley[8]. Less than 20 km north of the Lajas Valley, recent research has identified the surficial expressions of the Cordillera and Joyuda faults, which may be correlated with a WNW/ESE trend across southwestern Puerto Rico that is defined by a series of epicenters of small earthquakes that were recorded by the Puerto Rico Seismic Network in 1995[9]. Displacements along the potential fault(s) are unknown, but are likely to be small, given the evolution of the GPS baseline between distinct sites along the Puerto Rico coast (see below).

In addition, the island of Puerto Rico is traversed by two northwest-southeast striking fault zones: 1) the Great Northern Puerto Rico fault zone (GNPRFZ) and 2) the Great Southern Puerto Rico fault zone (GSPRFZ). The fault zones were active during the Eocene and record predominantly thrust and left-lateral displacement[10]. Field evidence for post-Oligocene motion along the fault is sparse, supporting a rigid PRVI since the Miocene. Both the GNPRFZ and the southern end of the GSPRFZ are covered by little deformed Neogene strata. The two fault zones, however, represent large areas of weakness within PRVI along which intrablock motion may be localized. Indeed, the southern end of the GSPRFZ immediately offshore may cut and disturb Recent shelf sediments [11, 12]. The projection of the northern end of the GSPRFZ, which continues offshore into Mona Canyon, is sub-parallel, however, to faults of similar orientation (NW/SE), which are seismically active [11, 13].

GPS data collection: Although the grant was not awarded until April 2000, we report on data gathered since October 1999. During the 2000 calender year, data were collected at 21 campaign sites in Puerto Rico and the Virgin Islands in addition to the three previously existing continuous sites (GEOL on the roof of the Physics building at UPRM and operated by us; PUR3 in western Puerto Rico and maintained by NOAA; and CRO1 in St. Croix and run by IGS). A continuous site was installed in Fajardo early in 1999 and another was established recently in San Juan. Of the 21 campaign sites occupied in 2000, nine were added to the network after the 1999 campaigns.

GPS campaign data were obtained with Trimble 4000 SSi 12-channel, dual-frequency, code phase receivers equipped with Trimble Dorn-Margolin type choke ring antennae. Data were collected and archived at a 30 s epoch using a 10° elevation mask. A minimum of 8 hours of GPS data per UTC observation day was collected during all campaign occupations. The majority of sites had more data as a result of 16-24 hours of observations during each UTC day. The University of Puerto Rico, Mayagüez (UPRM) (GEOL, FAJA, and UPRR), National Oceanographic and Atmospheric Administration (NOAA) (PUR3), and IGS (CRO1) continuous stations all have choke ring antennae and record at 30 s rate to 5° elevation. GEOL, FAJA, UPRR and PUR3 use Trimble 4000SSi receivers. The CRO1 site has an AOA Turbo Rogue receiver.

GPS data processing: GPS geodetic data were processed using the GPS inferred positioning system, orbit analysis, and simulation software package (GIPSY/OASIS II) developed, distributed, and supported by the NASA Jet Propulsion Laboratory (JPL) [(14)]. Analysis was performed either at the University of Puerto Rico, Mayagüez, using GIPSY (version 2.5, update 8a) along with various processing scripts. Receiver independent exchange (RINEX) format data were processed with precise orbit and clock products from JPL. A nonfiducial point-positioning strategy was adopted for all station days, following (3). Free-network solutions were transformed into the international terrestrial reference frame (ITRF96 initially and now ITRF97) [(15)]. Errors shown for daily site positions are scaled 1σ errors. Velocity estimates use a weighted least squares fit to daily site positions. Uncertainty on derived velocities reflects an estimate of both white and time-correlated noise, using the methodology of Mao et al., 1999[(16)].

RESULTS

Preliminary results are summarized below. Data from only a subset of the sites in the GPS network were used primarily due to the short time-series on many of the stations. A greater number of sites will be incorporated into the analysis next year as the time-series become sufficiently long to provide reliable results. We emphasize the analysis of GPS-derived velocities within a fixed North America reference frame. For more detailed discussion, the reader is referred to Jansma et al. (in press in Tectonics).

To describe the velocities of GPS sites in PRVI relative to the North American plate (Figure 2), we use the angular velocity that describes motion of the North American plate relative to ITRF96 (International Terrestrial Reference Frame 1996) to predict the North America ITRF96 velocity at each of our GPS sites. We then subtract the predicted plate velocity at each site from the site velocity and sum the covariance that describes the uncertainties in both. The North American plate angular velocity we use is derived from the velocities of 16 continuously operating GPS stations in the stable interior of the North American plate [(17)]. GPS-derived velocities are similar for all sites in Puerto Rico at the 95% confidence limit. The mean velocity for motion of PRVI relative to North America, computed for western Puerto Rico, is 16.9±1.1 mm/yr toward N68E±3 (1σ). At the same location, a new Caribbean-North America angular velocity derived from GPS sites in North America and the Caribbean plate[(7)] predicts that motion of the Caribbean plate relative to North America is 19.2±1.3 mm/yr toward N69E±3 (1σ). The velocity of PRVI with respect to North America is thus 2 mm/yr slower than that of the Caribbean plate at this location.

Comparison of Caribbean-North America motion in Puerto Rico to the mean velocity of sites in western Puerto Rico suggests that a minimum of 85% of the total motion between the North American and Caribbean plates at the longitude of western Puerto Rico is accommodated by faults north of Puerto Rico with the remainder accommodated to the south of the island.

The GPS-derived velocity with respect to North America at GORD in the British Virgin Islands of 19.5±2 mm/yr toward N75E±5° (1σ) closely approximates the predicted relative motion between the rigid Caribbean and North American plates at GORD, 19.4±1.3 mm/yr toward N68E±3° (1σ), and differs from the velocity of western Puerto Rico, 16.9±1.1 mm/yr toward N68°E±3° (1σ). With only two epochs of observations at GORD, the difference in the rates relative to North America of GORD and PRVI is barely above the 2 mm/yr level of the noise associated with GPS geodetic data. A third epoch of observations was obtained in 2000, but the data have yet to be processed.

The velocity estimate for sites in Puerto Rico yields errors that are < 2.0 mm/yr, defining the upper bound on permissible deformation within the island. All sites have velocities that are equivalent at the 95% confidence limit. The discrepancy in the velocities between Puerto Rico sites and GORD in Virgin Gorda at the eastern extreme of PRVI is close to the resolution of the current GPS geodetic data, giving relative motion between western (the island of Puerto Rico) and eastern (Virgin Gorda) PRVI at 3±3 mm/yr. Although the scatter of the GPS velocities on PRVI permits several millimeters per year of slip, the absence of any obvious geographic pattern in the velocities leads us to argue against substantial organized deformation within PRVI in favor of deformation slower than the several millimeters per year resolution of the present GPS velocities. We solved for a stronger upper bound on intra-PRVI deformation by examining the evolution of baseline length between the two continuous sites in western Puerto Rico, GEOL and PUR3 (Figure 3). Since continuous measurements began at both stations in June 1997, the baseline length has remained constant within error at -0.5±0.3 mm/yr (1σ). Intrablock deformation therefore is small; most deformation is likely accommodated along the bounding structures of the microplate. We note that the baseline between the two continuous sites crosses the GSPRFZ. Elastic strain effects from GSPRFZ on GEOL and PUR3 time series are unlikely. Simple two-dimensional elastic strain models using distances from GSPRFZ of 5 and 25 km for GEOL and PUR3, respectively, a baseline length change between GEOL and PUR3 of 0.5±0.3 mm/yr, and assumed vertical fault orientation with locking depths of 10-20 km suggest the permissible upper bound on GSPRFZ motion is 1.5±2.0 mm/yr.

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Jansma, P. E., G. S. Mattioli, A. Lopez, C. DeMets, T. H. Dixon, P. Mann, and E. Calais, Neotectonics of Puerto Rico and the Virgin Islands, northeastern Caribbean from GPS geodesy, Tectonics, in press

Lopez, Alberto, Models of microplate behavior in the northeastern Caribbean as constrained by GPS geodesy, MS thesis, University of Puerto Rico, Mayagüez, August 2000

DATA AVAILABILITY

The GPS data currently are being archived and are not yet available. Data processing and analysis also are not complete. When ready, the data will be placed in the UNAVCO archive following the standard procedures established by the GPS geodetic community. PUR3 and CRO1 data are available to anyone on-line through the standard archives.

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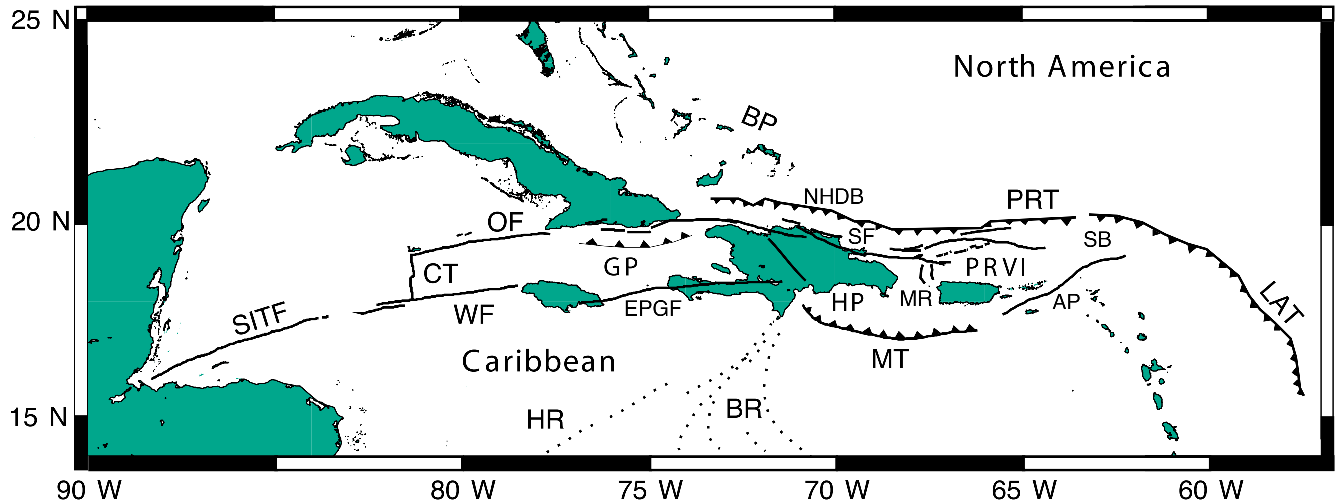

Figure 1: Map of northern Caribbean plate boundary showing microplates and structures. AP, Anegada passage; BP, Bahamas platform; BR, Beata ridge; CT, Cayman trough spreading center; EPGF, Enriquillo-Plantain Garden fault; GP, Gonave platelet; HP, Hispaniola platelet; HR, Hess rise; LAT, Lesser Antilles trench; MR, Mona rift. MT, Muertos trough; NHDB, north Hispaniola deformed belt; OF, Oriente fault; PRT, Puerto Rico trench; PRVI, Puerto Rico-Virgin Islands block; SB, Sombrero basin; SITF, Swan Islands transform fault; SF, Septentrional fault; SPRSF, south Puerto Rico slope fault; WF, Walton fault.

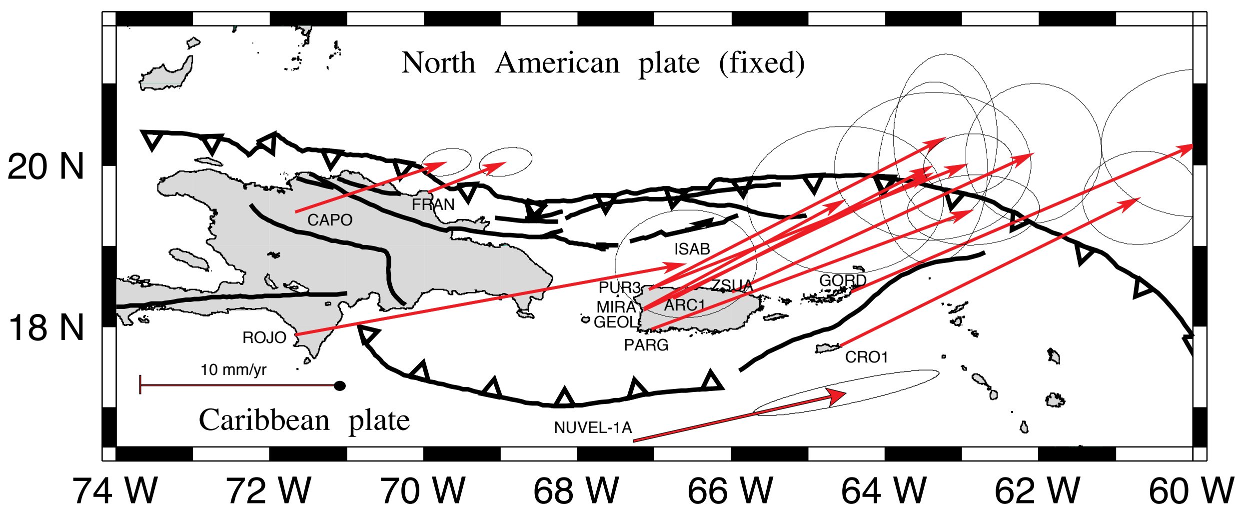

Figure 2: Velocities relative to North America defined according to DeMets and Dixon (1999). Confidence ellipses are 2D 95%.

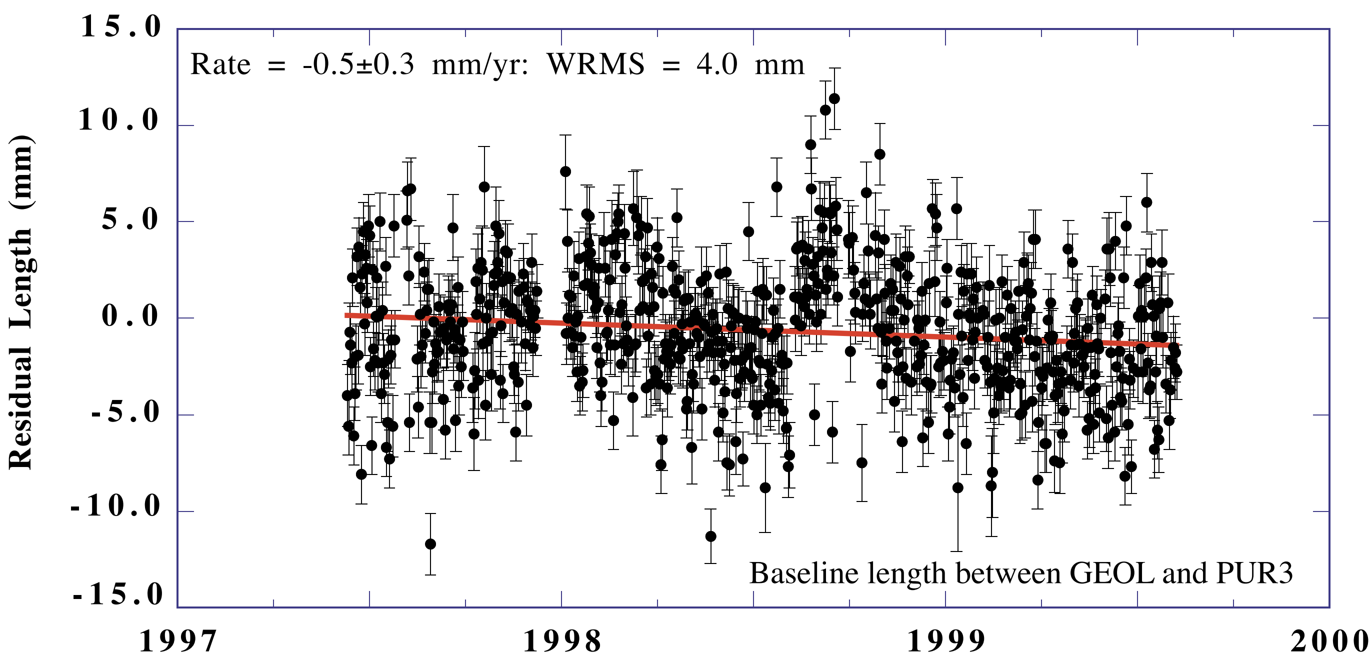

Figure 3: Evolution of residual baseline length between continuous sites PUR3 and GEOL from June 1997. Rate of change of the baseline is -0.5±0.3 mm/yr. Stated error is 1s formal error without any provision for monument noise. Median baseline length is 28898.713 m. Number of data points is 663.